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Resonant Magnon-Phonon Polaritons in a Ferrimagnet

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Abstract

The influence of a dynamic magnetoelectric interaction on TE and TM polaritons in a ferrimagnet in IR region of the spectrum has been considered. Frequency dispersions of dielectric and magnetic tensors were taken into account. Spontaneous magnetization induces an electric gyrotropy in a ferrimagnet and the additional radiant TM mode. In the presence of a constant electric field the possibility of a resonant interaction and transformation of the TM polaritons into the TE one and vice versa was predicted.

1. Introduction

In a magnet with more than one magnetic sublattice the exchange spin mode may be in the same IR region of the spectrum where there is an optical phonon mode. In this case it is necessary to take into account the frequency dispersions of dielectric and magnetic tensors simultaneousely. This situation was considered for polaritons in the cases when resonant (antiresonant) frequencies of dielectric and magnetic tensors are equal [1]. The appearance of the anomalous dispersion in the polariton spectrum was predicted.

We have considered the TE and the TM polaritons in a ferrimagnet in IR region of the spectrum in the cases of the different relations between the resonant and antiresonant frequencies of dielectric and magnetic tensors. The influence of a dynamic magnetoelectric (ME) interaction on TE and TM polaritons in a ferrimagnet was analyzed.

2. Energy and susceptibilities

For the example we consider a uniaxial ferrimagnet (z is an easy axis) with equilibrium antiparallel magnetic moments $\vec{M}_{10}, \vec{M}_{20}$ directed along z-axis, $M_{10} > M_{20}$. The density of the energy consists of a magnetic energy, electric dipole energy and the ME energy:

$$W = \Delta(\vec{M}_1\vec{M}_2) - \vec{h}(\vec{M}_1 + \vec{M}_2) + \frac{C_1}{2}P_z^2 + \frac{C_2}{2}(P_x^2 + P_y^2) - \vec{P}(\vec{E}_0 + \vec{e}) + \frac{1}{2\rho}\vec{\Pi}^2 + \frac{1}{c\rho}\vec{P}[\vec{\Pi} \times \vec{B}] \quad (1)$$

where $\vec{P}$ is the electric polarization, $\vec{\Pi}$ is the momentum density, $\vec{E}_0$ is a constant electric field, $\vec{e}$ and $\vec{h}$ are alternating electric and magnetic fields; $\rho = m/V_0$, m is the ion mass, V_0 is the volume of elementary cell; c is the velocity of light. Magnetic energy (two first terms) is written in exchange approximation, Δ >0 is the exchange constant. The last term in (1) is the dynamic ME energy [2].It is

the energy of the interaction of $\vec{P}$ with an effective electric field $E_{ef} = -(1/c)[\vec{v}\times\vec{B}]$ produced by the motion of charge e with velocity $\vec{v}$ in the media with magnetic induction $\vec{B} = \vec{h} + 4\pi(\vec{M}_1 + \vec{M}_2)$.

In the presence of a spontaneous magnetic moment $m = M_{10} - M_{20}$ the ME interaction induces the nondiagonal component of a dielectric tensor ε_{xy} and the precession of polarization around the direction of magnetic field. We obtain:

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_1 = \frac{(\Omega_1^2 - \omega^2)(\Omega_2^2 - \omega^2)}{(\omega_1^2 - \omega^2)(\omega_2^2 - \omega^2)}, \quad \omega_{1,2} = \omega_t \mp \omega_m, \omega_m = 4\pi g m_0, g = e/mc,$$
$$\varepsilon_{xy} = i\varepsilon' = -\frac{i8\pi\omega\omega_m\overline{\omega}_0^2}{(\omega_1^2 - \omega^2)(\omega_2^2 - \omega^2)} \tag{2}$$
$$\varepsilon_{zz} = \varepsilon_2 = \frac{\Omega_e^2 - \omega^2}{\omega_e^2 - \omega^2}, \quad \Omega_e^2 = \omega_e^2 + 4\pi\omega_e^2$$

with

$$\Omega_{1,2}^2 = \omega_t^2 + 2\pi\overline{\omega}_0^2 + \omega_m^2 \mp 2\sqrt{\pi^2\overline{\omega}_0^4 + \omega_m^2(\omega_t^2 + 2\pi\overline{\omega}_0^2)}$$

$$\omega_t{}^2 = C_2\overline{\omega}_0^2, \omega_e^2 = C_1\overline{\omega}_0^2, \overline{\omega}_0^2 = e^2/mV_0$$

Here ω_e is the excitation frequency of P_z, and ω_t is the excitation frequency of the P_x, P_y in the absence of a spontaneous magnetization. In IR region of the spectrum the expressions for the components of a magnetic tensor are following

$$\mu_{xx} = \mu_{yy} = \mu \cong \frac{\Omega_0^2 - \omega^2}{\omega_0^2 - \omega^2}$$
$$\mu_{xy} = i\mu' \cong \frac{i\omega_f(\Omega^2 - \omega^2)}{\omega(\omega_0^2 - \omega^2)} \tag{3}$$
$$\mu_{zz} = 1$$

with

$$\Omega_0^2 = \omega_0^2 + 4\pi\Delta M_{10}M_{20}(g_1 - g_2)^2, \omega_0 = \Delta(g_2 M_{10} - g_1 M_{20})$$

$$\Omega^2 = 4\pi\Delta g_1 g_2 m_0^2 \omega_0 \omega_f^{-1}, \omega_f\, 4\pi(g_1 M_{10} - g_2 M_{20})$$

where ω_0 is the exchange frequency, $g_{1,2}$ is the gyromagnetic relations for electron magnetic moments. The gyromagnetic relation for ion $g << g_{1,2}$. We consider the exchange constant $\Delta >> 1$. Thus, we have that $\omega_m << \omega_f << \omega_0 \sim \omega_t$. The relations $\varepsilon'/\varepsilon_1 \sim 4\pi\omega_m/\omega_t << 1$, $|\mu'/\mu| \sim \omega_f/\omega_0 \sim 4\pi/\Delta << 1$.

In the presence of a constant electric field $\vec{E}_o$ directed along x-axis the ME susceptibilities X_{xy}^{em} and $X_{xx}^{em} << X_{xy}^{em}$ appear, where

$$X_{xy}^{em} = \frac{\partial P_x}{\partial h_y} \cong \frac{igE_0\omega}{C_1(\omega^2 - \omega_t^2)} = \frac{i}{4\pi}\gamma \tag{4}$$

3. Phonon and magnon polaritons

We solve the Maxwell equations for the ferrimagnet with the dielectric, magnetic and ME tensors (2-4) for waves propagating in the direction of the x-axis ($k = k_x$)

In the absence of a constant electric field ($X^{em} = 0$) the TE and TM polaritons are independent.

In TM polariton wave e_x, e_y and h_z are not zero. The spectrum is described by the relation (see Fig.1)

$$\begin{gathered} k^2 = \omega^2 c^{-2}(\omega^2 - \tilde{\omega}_1^2)(\omega^2 - \tilde{\omega}_2^2)(\omega^2 - \Omega_1^2)^{-1}(\omega^2 - \Omega_2^2) \\ \tilde{\omega}_{1,2} = \Omega_t \mp \omega_m, \Omega_t^2 = \omega_t^2 + 4\pi\overline{\omega}_0^2 \end{gathered} \tag{5}$$

The frequencies $\tilde{\omega}_2, \Omega_2, \tilde{\omega}_1$ are closed one to another because $(\tilde{\omega}_2 - \Omega_2) \sim (\Omega_2 - \tilde{\omega}_1) \sim \omega_m$. In the absence of a magnetization $\tilde{\omega}_2 = \tilde{\omega}_1 = \Omega_2$ and there are two modes of TM polaritons. Thus, the ME interaction adds the new mode. This mode is a radiant one because of the possibility of a resonance interaction of this mode with the electromagnetic mode $\omega = ck$ (see Fig. 1).

In the TE polariton wave, h_x, h_y and e_z are not zero. The dispersion relation is

$$k^2 = \omega^2 c^{-2} \varepsilon_2 \mu^{-1}(\mu^2 - \mu'^2) \tag{6}$$

The spectrum consists of the three modes, which are similar to the shown one in figure 1. But these modes are not closed one to another. The value of the wave vector $k = 0$ if $\omega = \Omega_e$ and $\omega = \overline{\omega} = \Omega_0 + \omega_f(2\Omega_0^2)^{-1}(\Omega^2 - \Omega_0^2) \cong \Omega_0$. The wave vector $k \to \infty$ if $\omega = \Omega_0$ and $\omega = \omega_e$. The view of the polariton spectrum is the same as one in figure 1 but the disposition of the frequencies on the axis depends on the values of $\omega_e, \Omega_e, \omega_0$ and Ω_0. In the case when the phonon frequency ω_e is in the interval $[\omega_0, \Omega_0]$ the middle mode is the mode with anomaly dispersion. It exist in the interval $[\overline{\omega}, \Omega_0]$. So $\Omega_0 - \omega_0 \sim \omega_f$ in this case $\omega_e \cong \omega_0$.

4. Resonance of TE and TM polaritons

So the TM and TE modes belong to IR region of the spectrum the possibility of their crossover exists. For example, the intersection of the middle mode of the TE (TM) polaritons with another TM (TE) modes is possible. The exchange magnon frequency is often less than the mode of an optical phonon. Besides in a uniaxial crystal the value of ω_t is more than the value of ω_e. Then in the case when $\Omega_0 < \omega_e < \omega_1$ the crossover of the lower TM mode (Fig.1) with the middle TE mode is possible (the dashed curves in Fig. 2). Without a constant electric field the TE and TM modes do not interact.

In the presence of electric field $\vec{E}_0$ directed along the magnetization the interaction between the TE and TM polaritons appear due to the ME susceptibility (4). In the TM polaritons the fields h_x, h_y, e_z appear which are proportional to the small ME constant γ. So, we have

$$e_z = -\frac{\gamma[\varepsilon'\mu' + \mu(\varepsilon_1 - \nu^2)](\varepsilon')^{-1}}{\varepsilon_2(\mu^2 - \mu'^2) - \mu\nu^2} h_z, \quad \nu = ck/\omega \tag{7}$$

In the TE polariton excitations the weak fields e_x, e_y, h_z are induced by electric field. These additional fields are small far from the resonance of the modes. The resonance frequency ω_R is determined by the equation

$$\varepsilon_1\varepsilon_2\mu(\mu^2 - \mu'^2) = \varepsilon_1^2 - \varepsilon'^2 \tag{8}$$

Near the crossover the values of the additional fields in the modes increase (the dominator in (7) becomes a small) and the resonance interaction between the TE and TM polaritons takes place (Fig. 2). Thus, the resonance transformation of the TE(TM) polaritons into the TM (TE) one may be realized in the constant electric field.

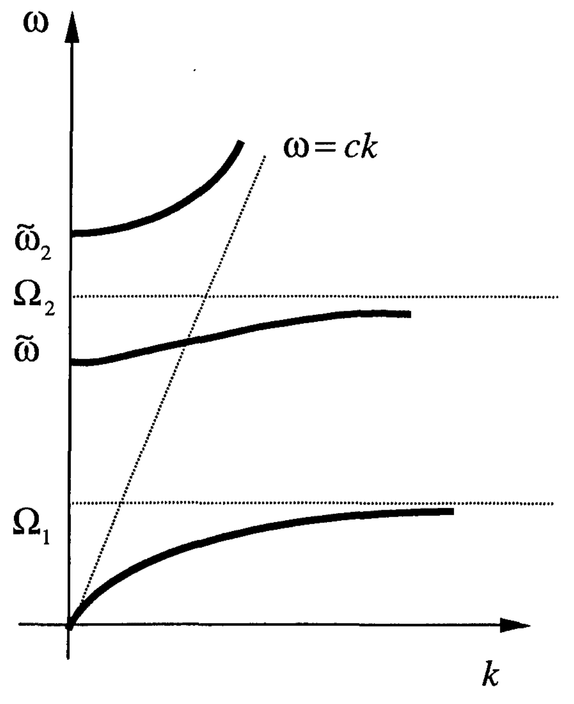

Fig. 1

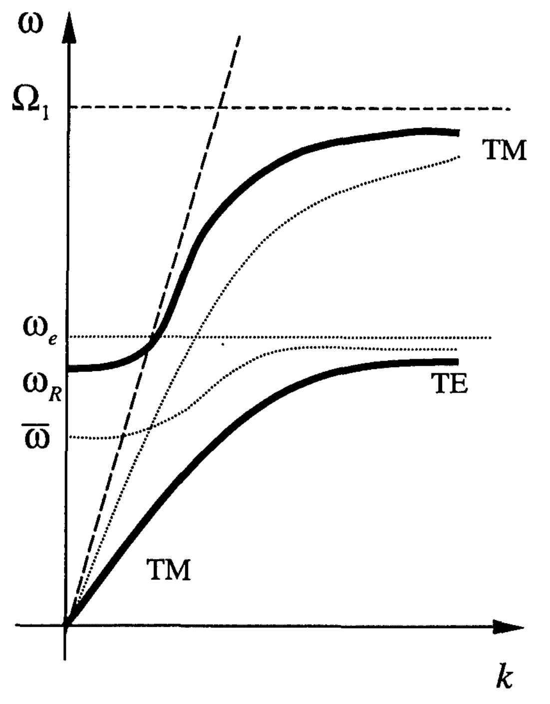

Fig. 2

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